



Composite Overwrap of a Lightweight, Additively Manufactured Thrust Chamber: Materials Characterization, Manufacturing, and Hot-fire Testing

Tyler Hudson (LaRC) | NASA SLAM²S Early Career Forum | NASA Stennis Space Center, MS | 09.28.2022

Co-Authors: Allison Clark (MSFC), Sandi Miller (GRC), Cheol Park (LaRC), Chris Stelter (LaRC), Sang-Hyon Chu (LaRC), Chris Protz (MSFC), Paul Gradl (MSFC), John Fikes (MSFC)

RAMPT Technology Overview



■ Project Description

- The Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project will mature novel design and manufacturing technologies to **increase scale**, significantly **reduce cost**, and improve performance for **regeneratively-cooled thrust chamber assemblies**, specifically the combustion chamber and nozzle for government and industry programs.

■ Technology Product Capability

- RAMPT project is developing and advancing multi-metallic freeform manufacturing, composite overwrap techniques, and analysis capabilities to reduce design and fabrication cycles for large-scale lightweight regeneratively-cooled liquid rocket engine components.
- RAMPT is reducing design, fabrication, assembly schedules while allowing for reduced parts, increased reliability, significant weight reduction and creating a healthy American supply chain.
- Four technology areas being developed: 1) Freeform blown powder nozzle; 2) **Composite overwrap structural jacket**; 3) Bimetallic radial deposition for manifolds; and 4) Modeling and analysis tools for additive and regeneratively-cooled design.

■ Sub-Project Objective

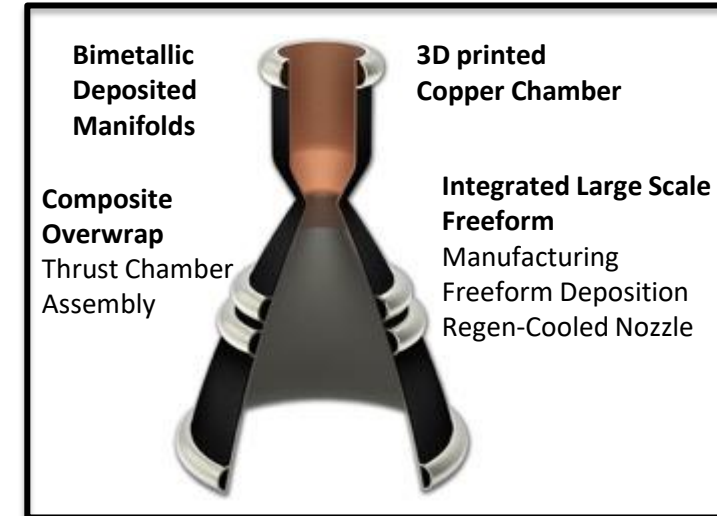
- Develop composite overwrap techniques to significantly reduce weight and provide structural capability for a large Thrust Chamber Assembly (TCA).

■ RAMPT Team:

- NASA Marshall Space Flight Center (MSFC), Langley Research Center (LaRC), Glenn Research Center (GRC), Ames Research Center (ARC), and many industry partners through a Public Private Partnership (PPP) with Auburn University.

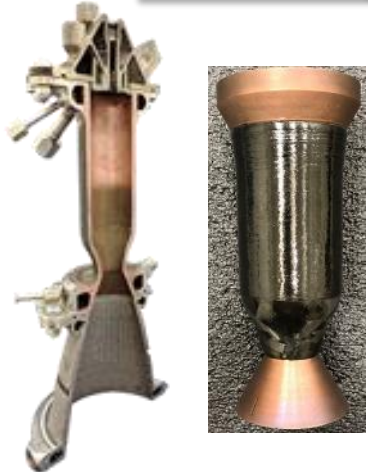
■ Customers:

- Game Changing Development (GCD), Space Launch System (SLS), DoD, space industry, and commercial companies.



Hardware Overview

2k-lb_f



Decoupled Chamber



Coupled Chamber

Engine Class:
Reaction Control Thrusters



7k-lb_f



Decoupled Chamber



Coupled Chamber

Engine Class:
Lunar (and Planetary) Landers



40k-lb_f



Decoupled Chamber

Coupled Chamber

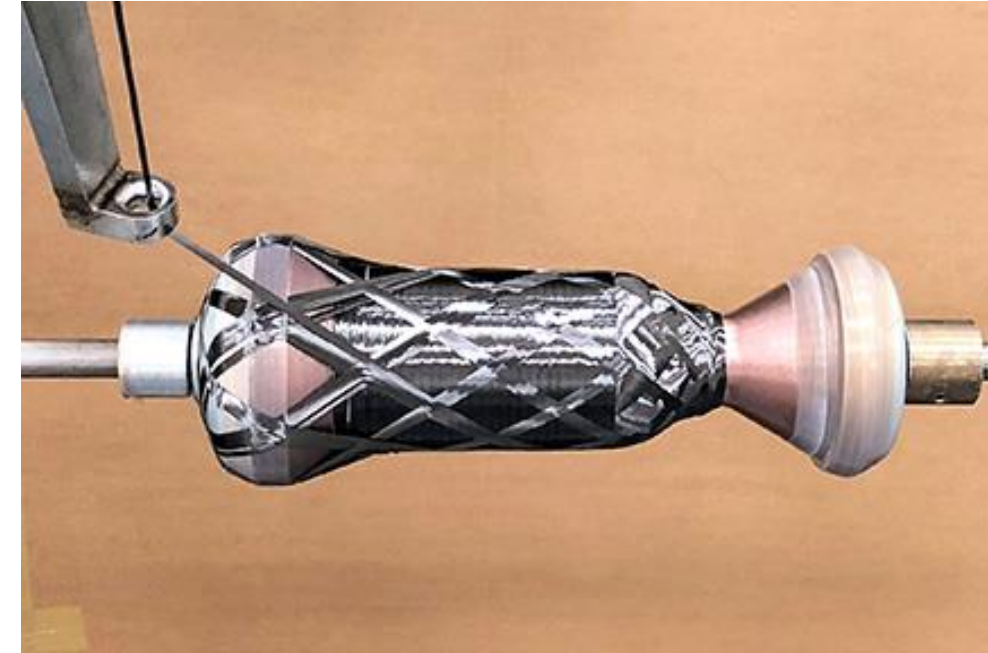


Engine Class:
Launch Vehicle (Upper Stage) and
Interplanetary Transport

Material Selection

Material Selection:

- Thermal requirements varied among the 2k, 7k, and 40k chambers:
 - 2k-lb_f (decoupled) is LOX/RP-1** fueled with composite overwrap interface temperatures of approximately **+70 to +250°F**
 - Multiple chambers were fabricated with several fiber/resin combinations
 - 2k-lb_f (coupled) and 40k-lb_f are LOX/LH2** fueled with composite overwrap interface temperatures of approximately **-400 to +150°F**
 - Hexion[®] 828/W epoxy resin with IM7G fiber utilized
 - 7k-lb_f is LOX/LCH4** fueled and has interface temperatures of approximately **-230 to +450°F**
 - High-end of the temperature range experienced by 7k chambers drove resin selection.
 - Eliminated toughened epoxies.
 - To accommodate both the upper and lower temperature extremes, Solvay[®] 5250-4 toughened bismaleimide (BMI) resin was selected.



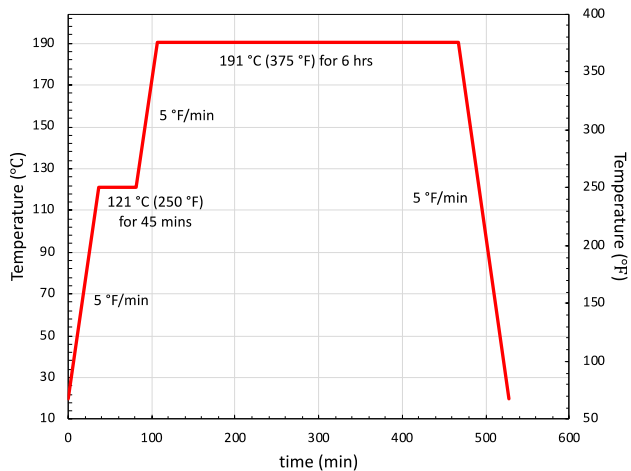
Dry Wind Trial of 2k-lb_f thrust chamber

LOX: Liquid Oxygen
RP-1: Rocket Propellant-1
(highly refined form of kerosene)
LH2: Liquid Hydrogen
LCH4: Liquid Methane

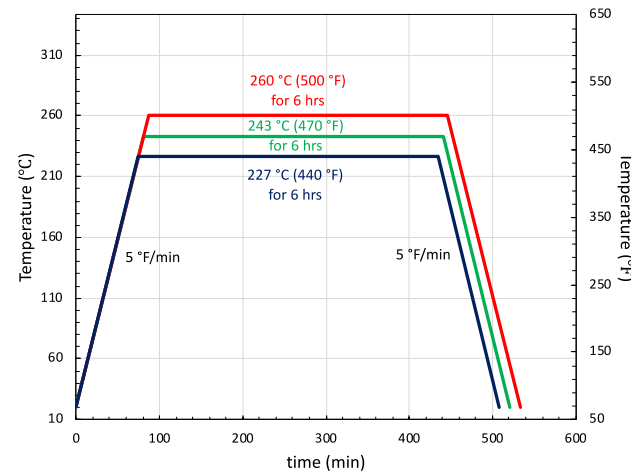
Materials Characterization of 5250-4 Resin

Materials Characterization: Dynamic Mechanical Analysis (DMA)

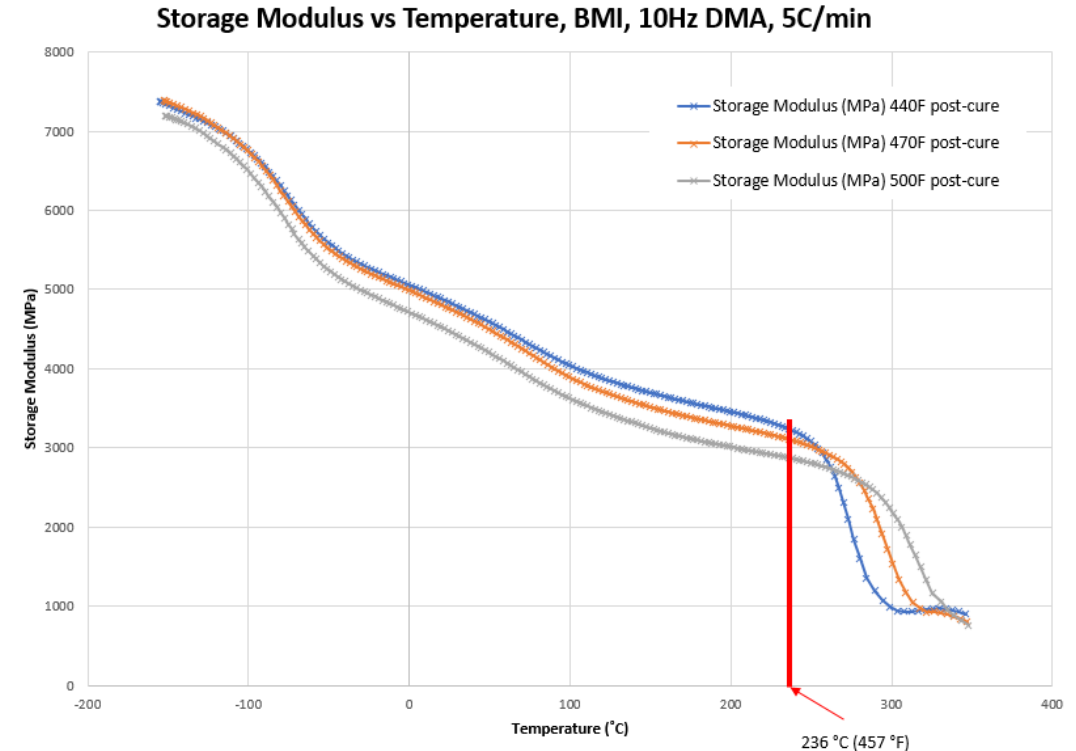
- Dynamic Mechanical Analysis (DMA) was performed on three post-cure conditions to determine the effect of post-cure temperature on modulus and glass transition temperature (T_g).



Standard cure cycle for 5250-4 BMI resin for the composite overwrap.



Post-cure cycles for 5250-4 BMI resin for the composite overwrap.



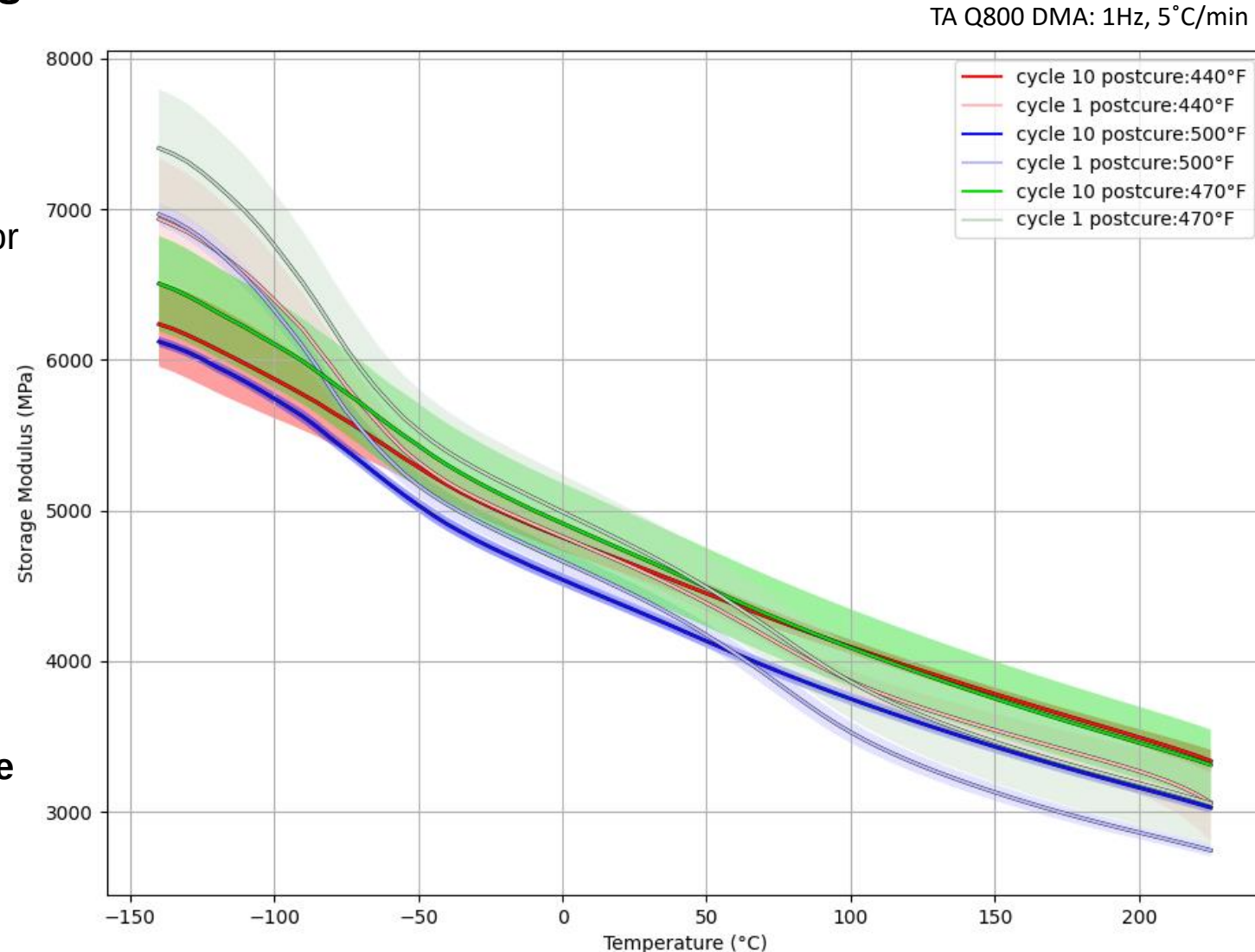
Summary of single cycle testing results:

- Resins with 227°C (440°F) and 243°C (470°F) post-cure had higher modulus for all temperatures until modulus drop than the 260°C (500°F) post-cure.
- Modulus dropped first for 227°C (440°F) post-cure, followed by 243°C (470°F) post-cure, then 260°C (500°F) post-cure.

Materials Characterization (*cont.*)

Storage Modulus from DMA Testing Runs

- DMA cycling tests (10 cycles) for three different samples (resin BMI 5250-4) for each post-cure temperature (440°F, 470°F, and 500°F) were completed.
- DSC tests for each sample were performed as well for comparison.
- Solid line represents average of 3 repeated cycling tests (cycles 1 and 10) for 3 post-cure temperatures. The error bars (or shaded regions) represent the average errors in 3 measurements.
- Storage modulus gradually decreased with increasing temperature.**
- Storage modulus decreased at low temperatures and slightly increased at high temperatures after cycling tests.**
- 470°F post-cure sample showed best performance throughout the entire temperature ranges and 10 cycling tests.**



Major Composites Processing Decision

Bond/No Bond Configuration:

- As-built, additively manufactured (AM) chambers have significant surface roughness.
- Curing the overwrap directly on the chamber would lead to a bonded overwrap.
 - Not ideal due to coefficient of thermal expansion (CTE) mismatch between the metallic chamber and the composite overwrap.
 - Metallic chamber would shrink and pull away from composite during curing and the initial cool-down of the hot-fire tests.
 - This could lead to delamination or tearing damage of a bonded composite.
- Not allowed to autofrettage as with traditional composite overwrap pressure vessels (COPVs).
- **Ultimately the decision was made for an unbonded overwrap.**
 - Consistent with thick-walled pressure vessels.
 - Procedure:
 - Chamber **surfaces polished with aluminum-free** (due to potential for hydrogen embrittlement) 80 grit then 120 grit sandpaper to remove surface roughness and oxidation.
 - Surfaces washed with ethanol, then treated with multiple coats of Frekote NC700 mold release agent.
- **Tradeoff: Metallic chamber must take entire pressure load until the composite overwrap is engaged.**

2k-lb_f Thrust Chamber Manufacturing

2k-lbf Decoupled Manufacturing:

- ~5 chambers manufactured and hot-fire tested (One configuration detailed below)
- Equipment: 4-axis filament winder and rotisserie oven
- Fiber: Hexcel® IM7, 12K tow carbon fiber
- Resin: EPON 828/W epoxy (2k chamber) resin.
- Resin Application Process: Wet wind with drum application
- Manufacturing Steps:
 1. Polish and apply release agent to chamber
 2. Apply 1st helical layer
 3. Apply 1st hoop layer (2-pplies)
 4. Apply 2nd helical layer
 5. Apply 2nd hoop layer (2-pplies)
 6. Trim overwrap from injector side of liner
 7. Rotisserie oven cure



Helical



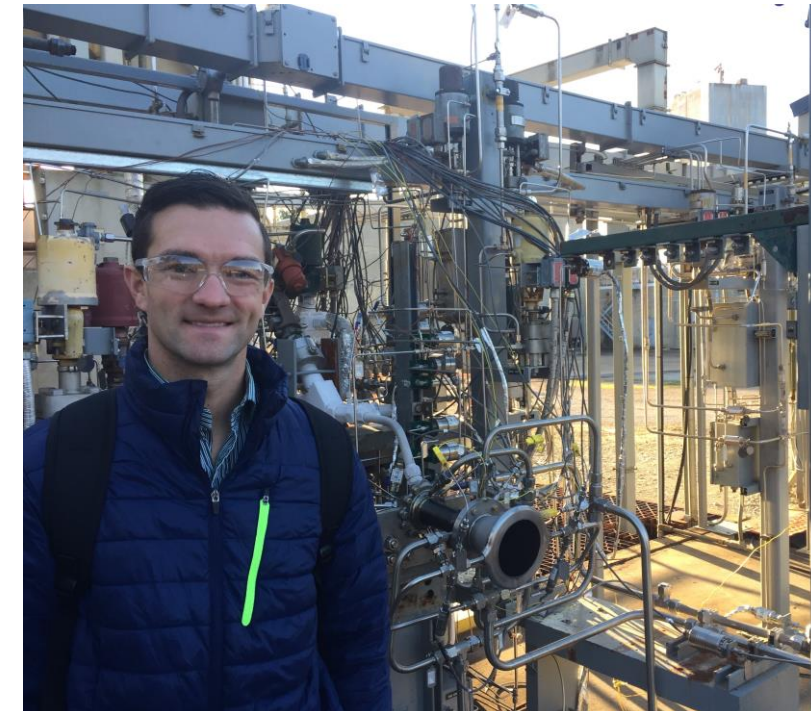
Hoop



Trimmed



Cured 2k-lb_f Chamber



Thrust Chamber Assembly at Test Stand

Hot Fire Test Video

2k-lb_f Thrust with LOX/RP-1

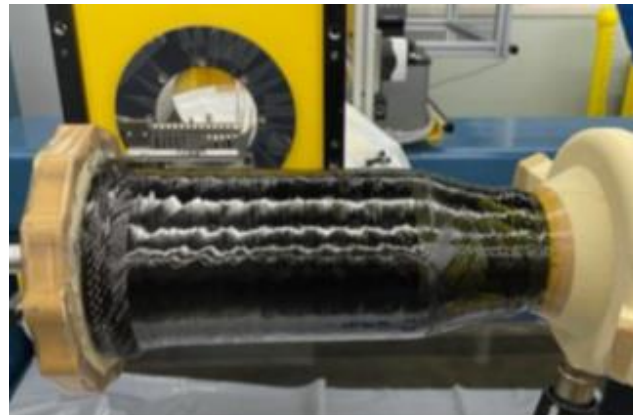


7k-lb_f Thrust Chamber Manufacturing

- Equipment: 4-axis filament winder and rotisserie oven
- Fiber: Hexcel® IM7, 12K tow carbon fiber
- Resin: Solvay® 5250-4 BMI resin
- Resin Application Process: Wet wind with manual application of resin (due to high processing temperature required by resin)
- Manufacturing Trials:
 - Dry-wind trials using a plastic 3D model
 - Wet-wind trials with partial cure using high temperature foam (FR-4718) closed cell polyurethane model that had been machined with a representative geometry.
 - Manufacturing trials allowed the team to practice the manufacturing process prior to arrival of hot-fire test articles. Helped ensure first-time part quality.



3D Printed Plastic Model



High-Temperature Foam Mandrel



Final Part

7k-lb_f Thrust Chamber Manufacturing



Surface Prep



Resin Application



Helical Layer



Completed Helical Layer



Hoop Layer



Completed Hoop Layer



Shrink Wrap

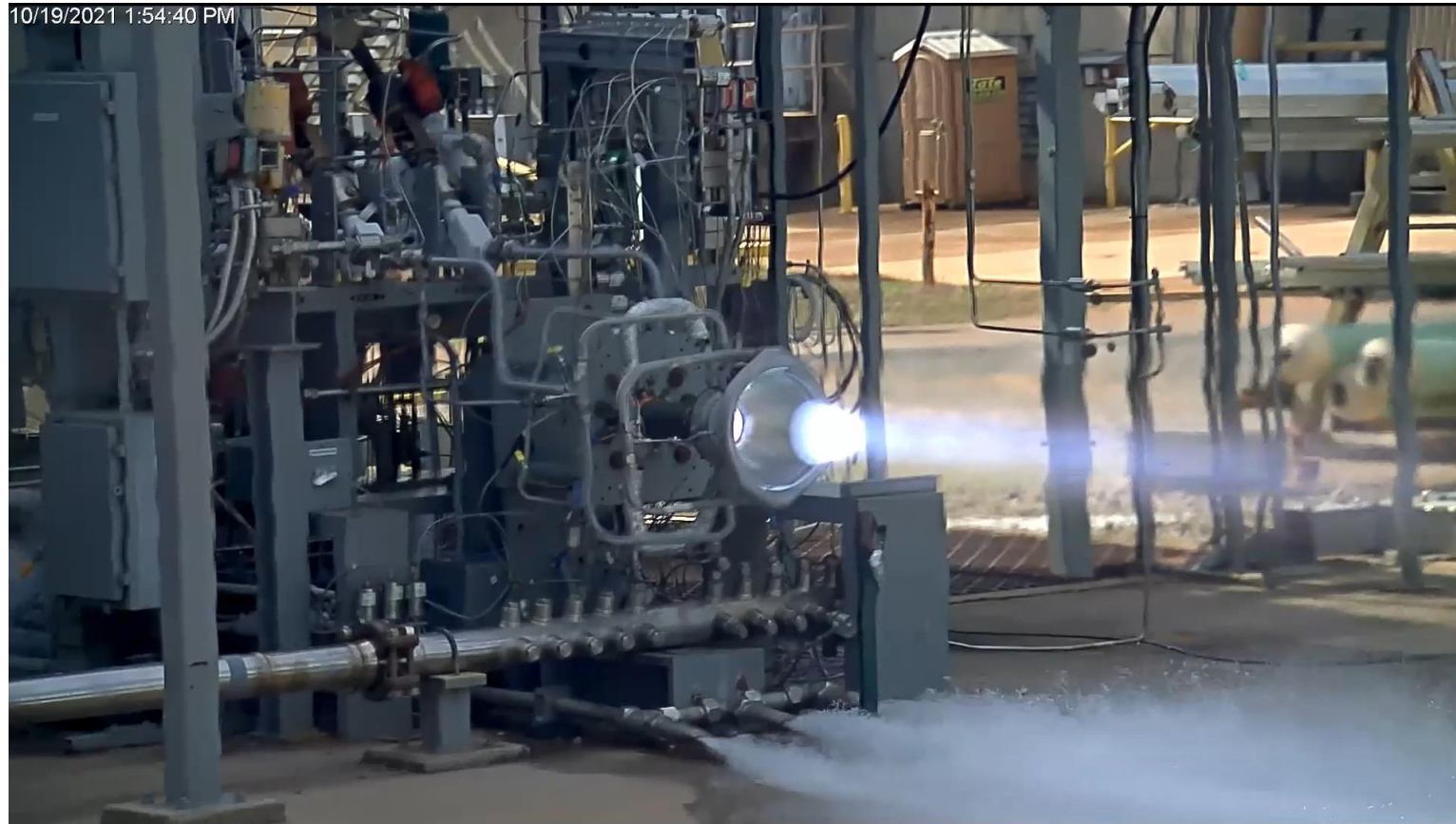


Part Before Oven

7k-lb_f Thrust Hot-fire Test Campaign

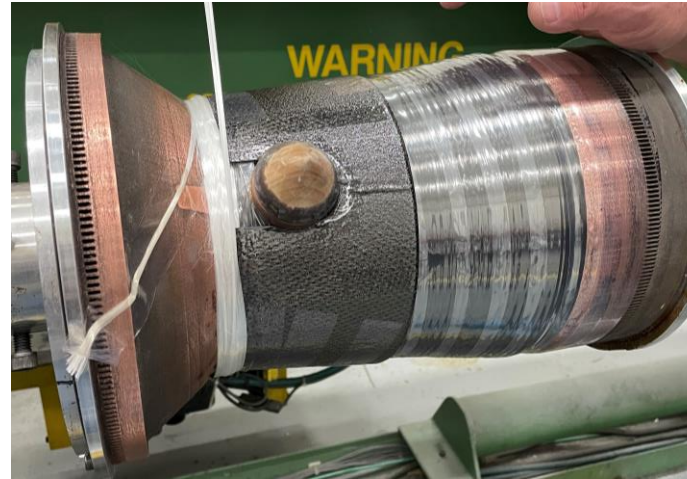
Testing Summary:

- Test Date: October 2021
- 7K-lb_f with LOX/Methane
- 13 starts at 351 seconds total duration
- 20 second firings at design pressure of 750 psia
- Final test achieved a chamber pressure of 790 psia with no issues to the chamber



40k-lb_f Manufacturing Trials

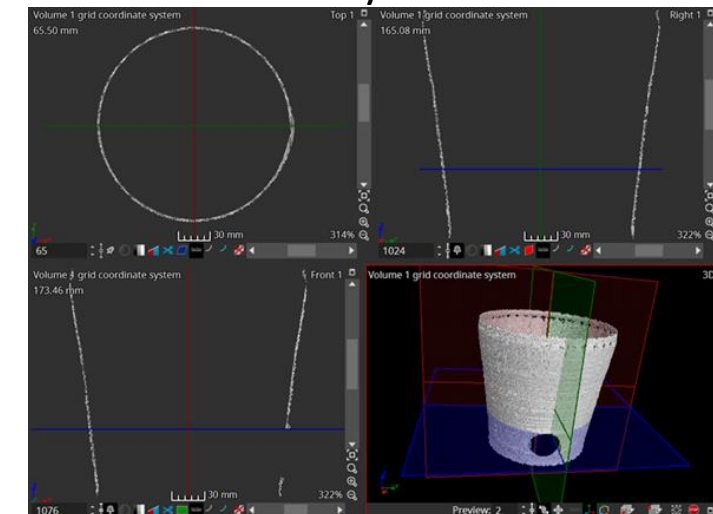
- **Completed wet wind trial on 40k-lb_f copper chamber** with improvements from previous trials.
- Material change introduced to assist manufacturing.
 - **IM7/8552 prepreg fabric and IM7/828W wet winding.**
- **Tooling change** made by adding rubber molding to the prepreg surface, using an in-house built caul sheet, and adding a layer of fabric tension on top of the layup.
- Improvements resulted in better resin consolidation, no gap in the winding on the back side of the chamber, and no wrinkles in the prepreg.
- X-Ray Computed Tomography (CT) used to determine thickness and quality of the composite overwrap.
- **Infrared flash thermography** used to determine the degree of contact between composite overwrap and base material.



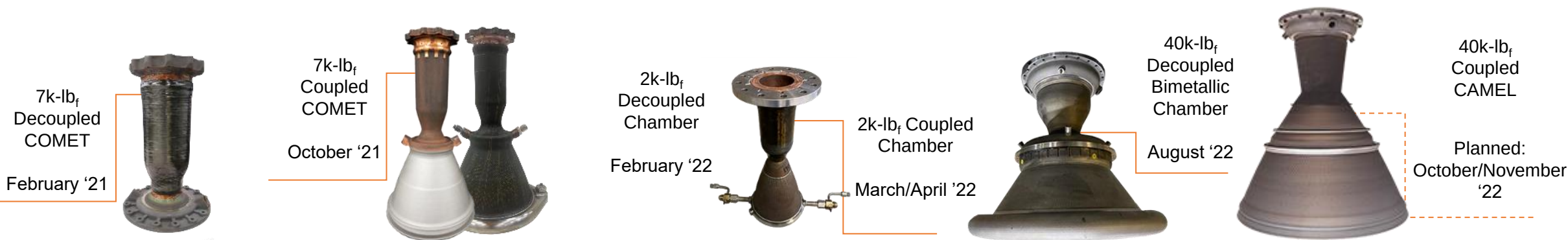
Flash Thermography



X-ray CT



Hot Fire Tests (2021 and 2022)



2021

2022

J M A M J J A S N D J A M J J S O N D

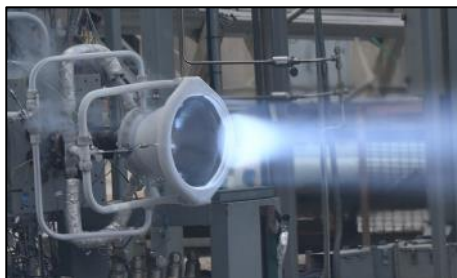
7k-lb_f Decoupled



COMET: Composite Overwrapped Methane Engine Thruster

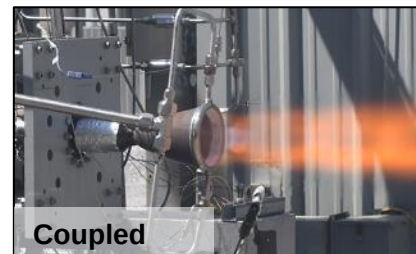
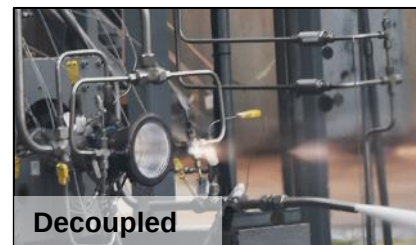
Composite Overwrap Winding

7k-lb_f Coupled



Composite Overwrap Braiding

2k-lb_f Decoupled & Coupled



Composite Overwrap Winding

40k-lb_f Decoupled & Coupled



Future Tests

40k-lb_f Coupled CAMEL:
October/November '22

CAMEL – Composite-overwrap Additive Manufactured assembly Evaluated at Large-scale



Composite Overwrap Winding

2k-lb_f and 40k-lb_f are LOX/LH₂ and have composite overwrap interface temperatures of -400 to +150°F

7k-lb_f COMET hardware is LOX/LCH₄ and has interface temperatures ~-230 to +450°F

Summary

- The NASA Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project aimed to develop efficiency improvements to the longest lead, highest cost, and heaviest components in a rocket engine.
- Developed an optimized, large-scale, multi-metallic, regeneratively-cooled, additively-manufactured thrust chamber assembly with a composite overwrap jacket structure.
- Composite overwrap demonstrated greater than 50% weight savings compared to state-of-the-art nickel alloy clad chambers.
- Three engine classes have been fabricated: 2k-lb_f (reaction control), 7k-lb_f thrust (human/cargo lunar landers), and 40k-lb_f thrust (upper stage launch vehicles and interplanetary transport) for use with three fuel types [kerolox (RP-1/LOX), methalox (LCH₄/LOX), and hydrolox (LH₂/LOX)].
- 2k-lb_f and 7k-lb_f thrust chamber assemblies have been successfully hot-fired. Hot-fire of 40k-lb_f thrust assembly scheduled for later this year.

RAMPT Composite Overwrap Team

NASA

- Composite Overwrap Team: Tyler Hudson (LaRC, Co-Lead), Allison Clark (MSFC, Co-Lead), Sandi Miller (GRC), Cheol Park (LaRC), Chris Stelter (LaRC), Sang-Hyon Chu (LaRC), and John Thesken (GRC)
- RAMPT Co-Principal Investigators: Paul Gradl (MSFC) and Chris Protz (MSFC)
- Project Manager: John Fikes (MSFC)
- Project Coordinator: Lynn Machamer (MSFC)

Kord Technologies

Composite Overwrap of a Lightweight, Additively Manufactured Thrust Chamber

Questions?